DRAFT 4
ARRL Ex Parte Presentation[1]
to the Office of Engineering and Technology
Federal Communications Commission
March 22, 2002

Summary

ARRL, the National Association for Amateur Radio, has provided the Commission data in several previous *Ex Parte* presentations related to ET Docket 01-278, "Review of Part 15 and Other Parts of the Commission's Rules." These presentations were intended to demonstrate the variation in field strength and received signal levels (RSL) with distance from a radiating source.

The Reply Comments filed by Savi Technologies, however, reiterated its their position that the standard path loss formulae that ARRL used are in error by over 30 dB. In its Reply Comments, Savi described a complex two-step process that it asserts is what one "must" use to obtain the correct RSL. Savi's calculations are, however, incorrect. Savi's method assumes that the calculation made of RSL at a point 3 meters from the radiating source somehow causes the flow of power from the source toward that point that created the field present at that point to be isotropically re-radiated. This represents a 30-dB error on Savi's part. Savi's 30-dB underestimation of the fields that will occur near a radiator that is creating fields of 110,000 □/m at 3 meters means that such a signal will propagate for a distance that is 30 times what Savi estimates. Clearly, Savi's misapplication is the fundamental reason that ARRL and Savi reach such widely differing conclusions about the effect of the signals the rules propose. If they are underestimating their own signal strength by more than 30 dB, clearly they do not need the levels they propose and the harmful interference that will result from such RFID signals would be more than 1000 times higher than they believe.

The following discussion outlines the correct way to make RSL calculations. It compares those calculations to identical results using commercial software packages that predict field strength from radiating sources, followed by practical and mathematical demonstrations that explain why Savi's methods provide inaccurate results.

[1] This is a written Ex Parte presentation, prepared by ARRL Laboratory Supervisor Ed Hare and Senior Engineer Zack Lau.

A Correct Method to Calculate Received Signal Levels:

The easiest way to determine the received signal level (RSL) in free space at a point distant from a radiating source is to apply the formula:

Path loss (dB) = 32.45 + 20log D(km) + 20log F(MHz) (See footnote [2]) [Equation 1.0]

This is the formula ARRL used to determine the RSL at 3 meters, 100 meters and the other points on the graphs it has supplied to the Commission, starting with a –24.4 dBW EIRP, producing a 110,000-microvolt/meter field 3 meters from the source.

In table form, the results are:

RSL(dBW) = -24.4 dBW – (32.45 + 20log (0.003) + 20log (433.92)) = -59.14 dBW at 0.003 km
RSL(dBW) = -24.4 dBW – (32.45 + 20log (0.006) + 20log (433.92)) = -65.16 dBW at 0.006 km
RSL(dBW) = -24.4 dBW – (32.45 + 20log (0.100) + 20log (433.92)) = -89.60 dBW at 0.100 km
RSL(dBW) = -24.4 dBW – (32.45 + 20log (1.000) + 20log (433.92)) = -109.60 dBW at 1.0 km

These calculations are based on the standard practice that the field strength and RSLs at a distant point are easily calculated based *on the distance from the radiating source.*

In graphical form, here are the results of the calculations of RSL levels from a –24.4 dBW EIRP source that ARRL provided in its earlier Ex Parte presentations:

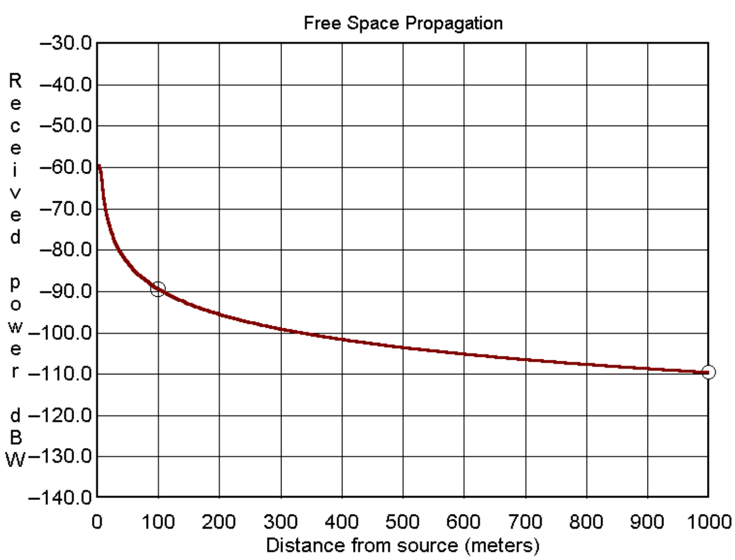

Figure 1. This is the 0 dBi data from ARRL's earlier Ex Parte presentations. The graph shows the amount of power that will be picked up by an isotropic antenna located the specified distances from 3 to 1000 meters from a –24.4 dBW source that is producing 110,000 □/m at a point 3 meters from that source. The circles represent ARRL calculations for 100 and 1000 meters from the radiating source. This follows a 20 log (distance ratio) function.

[2] This formula is derived from the Friis transmission equation. Reference Friis, H.T., "A Note on a Simple Transmission Formula," Proc. IRE, 34, p 254-256, 1946. Reference also Krauss, John D., *Antennas,* second edition , McGraw Hill, NY, 1988.

To facilitate the following discussion, the following graph shows the data from Figure 1 above, converted to field strength in volts/meter.

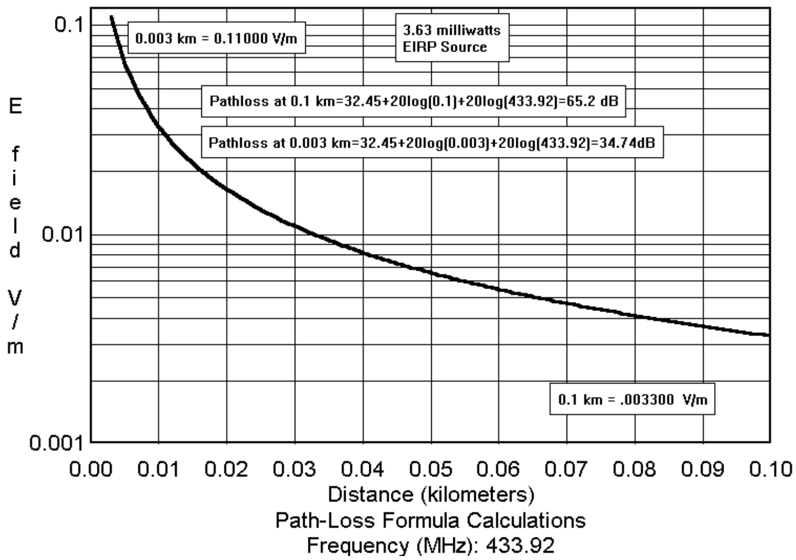

Figure 2. This is the calculated field at various distances from a –24.4 dBW isotropic source, in volts/meter.

ARRL Calculations are in Agreement with Commercial Software Packages:

The method that ARRL used to derive its data is in excellent agreement with independent data and results from EZNEC[3] Pro Version 3.0.10 (NEC-4 engine) and from calculations provided to ARRL by Dr. Arthur W Guy[4], Ph. D, using Remcom Inc's[5] XFDTD Version 5.3.0.2 finite difference time domain (FDTD) electromagnetic simulation program. Both programs were used to predict the electric field strength in free space from a –24.4 dBW EIRP radiator.

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[3] Eznec, Roy Lewallen, PO Box 6658, Beaverton, OR 97007, USA, Tel: 503-646-2885, Fax: 503-671-9046, Email: w7el@eznec.com, http://www.eznec.com

[4] Guy, Arthur W., Ph. D, 18122 60th Place NE, Kenmore, WA 98028-8901, http://www.arrl.org/rfsafety/w7po_cv.html

[5] Remcom, Inc., 315 South Allen Street, Suite 222, State College, PA 16801, http://www.fdtd.com/html/index.html

The results of the calculation made by EZNEC Pro have been graphed in Figure 3.

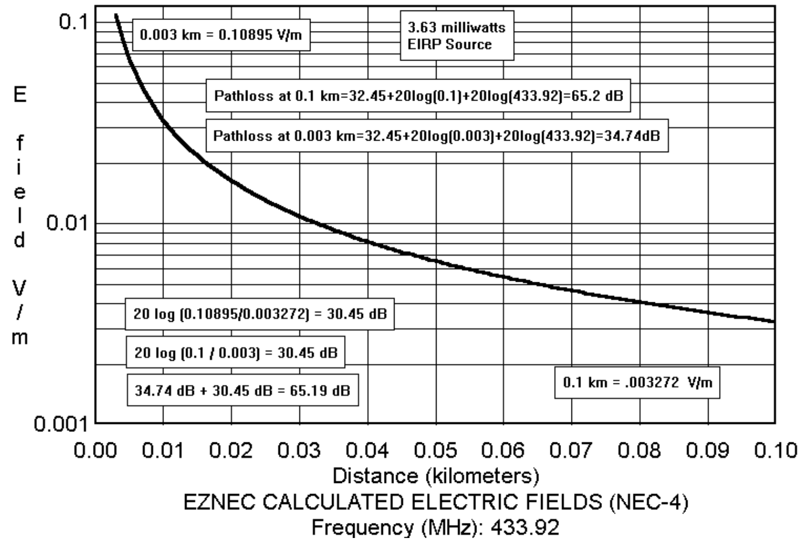

Figure 3. This is the field strength predicted by EZNEC Pro from a source radiating –24.4 dBW EIRP on 433.92 MHz. The RMS field strengths predicted by NEC-4 are identical to that predicted by the path-loss formula.

The results of the XFDTD calculation made by Dr. Guy are shown in Figure 4.

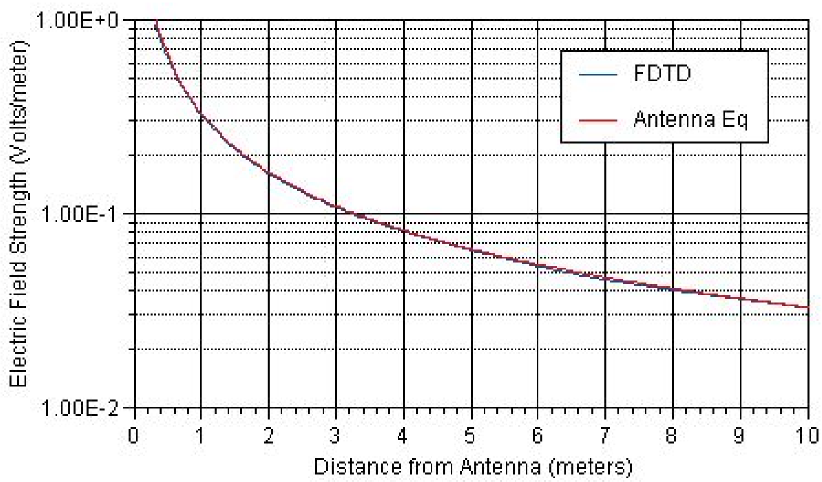

Figure 4. The free-space field strength from an electrically short dipole radiating –24.4 dBW EIRP, predicted by XFDTD, an FDTD electromagnetics program graphed by Dr. Guy using the Delta Graph graphing software package.

There are actually two lines, one on top of the other, on the graph in Figure 4. The one line is the FDTD analysis and the other line is the result calculated using the antenna equation that is used to calculate the field strength at one location based on the result at another.

The field strength calculations from EZNEC Pro, XFDTD and ARRL's data are virtually identical. Although each method uses very different techniques to arrive at the end result, the correlation is not at all unexpected, as all three methods are based on well-accepted principles. The Savi calculations for RSLs at 100 meters and 1000 meters separation are more than 30 dB below these modeling results.

Savi's Calculations:

In its Reply Comments, Savi claims that to "determine the received signal levels at various distances from the source in dBm or dBW, one must use the following process: " Savi then describes steps to convert field strength to an RSL, then incorrectly apply the path-loss formula *to that calculation* to predict the path loss at another distant point.

This method is incorrect. There is a simple, well-understood method to predict the RSL at a distant point – apply the path loss formula to the EIRP (or to the transmit power and factor in the antenna gain of the transmitter and receiver). The two-step process that Savi uses is not only unnecessary, but gives incorrect results that do not follow a 20 log (distance from the radiating source) function.

In using the method they describe, Savi is essentially using the path loss formula twice. The first is by definition in defining a field of 110,000 □/m as being 3 meters from a radiating source. The second is by assuming that the received signal power *calculated* at that 3 meter point will somehow be isotropically radiated all over again (there is no physical mechanism by that would cause this to happen) rather than continuing as a flow of power toward a distant source. Using the path loss formula twice results in a significant underestimation of the field and RSL at a distant point.

The path-loss formula includes a distance factor and a frequency factor, both expressed as 20 log. The 20 log (distance) factor accounts for the fact that the electric field strength from an antenna in the far field region is inversely proportional to distance. (In the far-field region, this is independent of frequency.) The 20 log (Frequency) function in the formula accounts for the fact that the capture area of an isotropic antenna is a function of λ^2, so the capture area of an antenna varies with frequency. This can be visualized in Figure 5. As can be seen in this figure, the 20 log (F) function is a simple matter of the geometry of the capture area of an antenna as a ratio to the area of a sphere of the same radius as the distance from the radiating source.

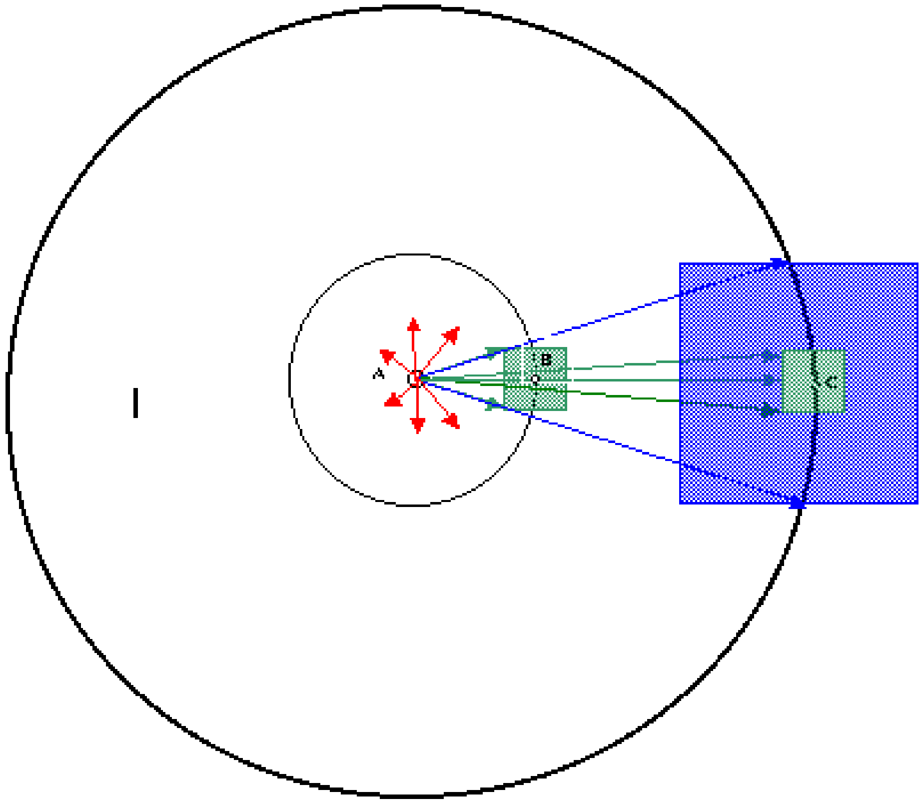

Figure 5. This graphic visualizes the flow of power from a source at Point A to antenna apertures (green) located at Point B and Point C and the relationship between the geometry involved and the path-loss and Friis formulae.

Although there are more complex ways of making the calculations, the easiest way to determine the RSL to an isotropic antenna at a point distant from the source (Point A) is to apply the path loss formula of Equation 1.0 to determine the amount of power that will be received. For example, to calculate the RSL at an isotropic antenna at point B, this formula correctly expresses the ratio of the power received in the capture area of the isotropic antenna to power radiated to the entire area of a sphere of radius AB by the isotropic source at Point A.

The amount of power received at Point C is determined by the ratio of the capture area of the antenna at Point C to the area of a sphere with a radius AC. Figure 5 demonstrates visually that all of the power that would have been captured by the antenna at Point B continues to flow outward toward Point C, spreading out to the size of the larger rectangle. (Why would it not? The only thing that has been done at Point B to set the regulation at 110,000 □/m peak is to make a calculation.) An antenna placed at Point C will capture a portion of this flow of power because the power is continuing to spread as it radiates from the source. For antennas of equal capture area, the ratio of the power in antenna C compared to antenna B is easily determined by taking the ratio of the squares of the distances involved. Expressed in decibels, this is a 20 log (distance ratio) function, a factor that perfectly describes the geometries involved. So the amount of power captured by an antenna at Point C will be 20 log (AC/AB) *less* than the amount of power captured at Point B. This is commonly referred to as "spreading loss."

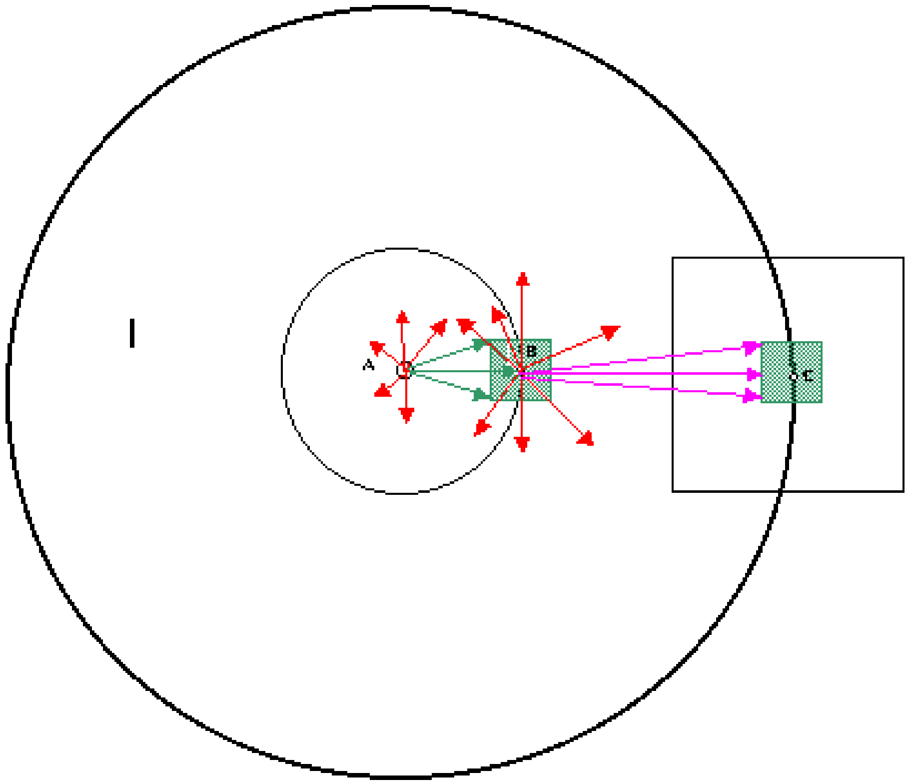

Figure 6. This shows the effect that is described by the method that Savi incorrectly used to determine path loss to Point C. Such re-radiation does not happen simply as a result of making a calculation at Point B.

Figure 6 shows the process that Savi used to arrive at its inaccurate results to calculate the RSL of an isotropic antenna at Point C. In using that method, Savi assumed that making a calculation of the power that would be received by an antenna at Point B somehow causes that energy to be re-radiated isotropically from that point rather than continuing as a flow of power from Point A outward toward Point C. While this effect can happen if a mountain or other obstruction prevents the radiation from Point A from arriving directly at Point C, merely making a calculation at some point along the path does not result in such scattering.

A Point of Agreement

ARRL and Savi are in reasonable agreement that the radiating source is 3.63 mW EIRP (-24.4 dBW). This radiated power level produces a field strength of 110,000 μV/m at 3 meters distance.

The calculated path loss for a distance of 3 meters is:

Path loss (dB) = 32.45 + 20 log (0.003) + 20 log (433.92) = 34.74 dB

One can then calculate the RSL at a point 3 meters from the radiating source by using two relatively easy methods, both of which are mathematically equivalent, derived from the same fundamental principles: (The slight difference is due to rounding on the –107 dB.)

ARRL: RSL dBW = -24.4 dBW – 34.74 dB = -59.14 dBW
Savi: RSL dBW = -107 + 20 log (110,000) – 20 log (433.92) = -58.92 dBW

A Point of Departure

Savi then incorrectly claims that one can use the path loss formula to calculate the RSL at another point by using the RSL from the first calculation (the point 3 meters from the radiating source). To demonstrate that this is incorrect, one can analyze the results of that second point being set 3 meters distant from the 110,000 μV/m field — a total of 6 meters from the radiating source. Savi's method claims that at a point 3 meters distant from the point that the field is 110,000 μV/m, the field will drop by another 34.74 dB. One has doubled the distance, yet decreased the field by 34.74 dB.

This error should be apparent as the field strength from a radiating source varies inversely with distance (a 20 log (distance) function for electric or magnetic fields). Doubling the distance should have decreased the field by 6.02 dB, giving the correct RSL at 6 meters distant as –65.16 dBW (in agreement with ARRL's calculations on the first page.)

Total Power Does Not Add Up – Power Density on a Sphere:

Savi reasonably accurately calculates that the RSL at 3 meters, with a field of 110,000 μV/m, will be -58.17 dBW. They then incorrectly calculate the RSL at a point 100 meters away from the source by again applying the path loss formula from that point to the more distant point:

RSL = -58.17 – (32.45 +20 log (0.097) + 20 log (433.92)) = -122.57 dBW

This Savi calculation is about 30 dB less than what is obtained using the path loss formula based on the distance from the radiating source. That this is true can be demonstrated by dividing the RSL by the capture area of an isotropic antenna on 433.92 MHz (0.038 meters^2), to obtain the power density, and then multiplying the power density by the area of a sphere of the same radius as the distance calculation. If everything was calculated correctly, the result should be equal to the applied EIRP. When this is done, the numbers that Savi claims for RSLs for 100 and 1000 meters distance from the source do not add up to the total power being applied to the system.

In the case of a field of 110,000 μV/m 3 meters from the radiating source, the radiated power level is –24.4 dBW EIRP. Some of the steps of this analysis are easier to follow in millwatts, so the following discussion will be based on 3.63 mW.

A sphere of 3-meters radius has a surface area of

$$\text{Area of sphere} = 4\pi R^2 = 4 * 3.14159 * (3^2) = 113.097 \text{ meters}^2$$

If isotropic, the 3.63 milliwatts will be evenly spread across 113.097 meters^2 at a power density of:

$$3.63 / 113.097 = 0.0321 \text{ milliwatts/meter}^2$$

This power density is equivalent to a field of 110,000 microvolts/meter.

The capture area of an antenna is:

$$\text{Capture area} = G\lambda^2 / 4\pi \quad G=1 \text{ for an isotropic antenna} \qquad \text{[Equation 1.1]}$$

λ in meters = 300 / FMHz, thus:

$$\text{Capture area} = (\ (300/433.92)^2\ ) / (4 * 3.14159) = 0.038 \text{ meters}^2. \text{ (See footnote}^6.)$$

The power received by an isotropic antenna located 3 meters distance from a 3.63 milliwatt EIRP source is:

$$0.038 \text{ meters}^2 * 0.0321 \text{ milliwatts/meter}^2 = 0.00122 \text{ milliwatts} = -59.14 \text{ dBW}.$$

One can then multiply the power density, 0.0321 mW/m^2, by the volume of the 3-meter sphere, 113.097 meters^2 to obtain source power of 3.63 mW. ARRL and Savi agree on the source power and the RSL at 3 meters distance, within calculating rounding errors.

Savi Calculations for RSL at 100 Meters and 1000 Meters are Incorrect:

To see why the Savi calculation for RSL at 100 meters from the source cannot be correct, it is necessary to repeat the process for 100 meters separation from the radiating source.

$$\text{Area of sphere} = 4\pi R^2 = 4 * 3.14159 * (100^2) = 125663.6 \text{ meters}^2$$

An easy way to calculate the RSL at a different distance is to use the ratios of the distances involved. If the area of the sphere is increased from 113.097 meters^2 to 125663.6 meters^2, with the power being radiated isotropically in both cases, the power density at an isotropic antenna at the two distances will be a ratio of (113.097 / 125663.6) meters^2 or 10 log (113.097 / 125663.6) or -30.45 dB. Thus, the power received at 100 meters distance will be 30.45 dB less than the power at 3 meters distance, or -59.17 dBW - 30.45 dB = -89.68 dBW. This is, not coincidentally, related to the factor of 20 log (actual distance / reference distance) that was correctly described in Equation 1.0 of ARRL's earlier Ex Parte presentation.

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[6] It is necessary to observe the order of operations here; without the parenthesis one will get the wrong capture area.

The validity of the calculations ARRL has done can be demonstrated as follows:

At 100 meters separation, the 3.63 milliwatts isotropic at the source will be evenly spread across 125663.6 meters^2 and will result in a power density of:

$$3.63 / 125663.6 = 0.00002889 \text{ milliwatts/meter}^2 \text{ at a distance of 100 meters}$$

The capture area of the 433.92 MHz isotropic antenna doesn't change, so the captured power is:

$$RSL = 0.038 \text{ meters}^2 * 0.00002889 \text{ milliwatts/meter}^2 = 0.000001098 \text{ milliwatts} = -89.59 \text{ dBW}$$

This can be calculated in reverse to obtain the applied isotropically radiated power:

$$0.00002889 \text{ milliwatts/meter}^2 * 125664.6 \text{ meters}^2 = 3.63 \text{ milliwatts.}$$

If we take the figure that Savi had calculated at 100 meters distance, -92.57 dBm (-122.57 dBW), this is 5.53E-10 mW. One can divide this by the capture area to get a power density of 1.456E-8 mw/meter^2. If this is multiplies by 125663.6 meters^2, one would get 0.00182 mW, or -57.38 dBW, not the 3.63 milliwatts or –24.4 dBW of the isotropically radiating source. Savi's error is -32.98 dB.

Concluding Remarks

If, as Savi claims, path loss calculations can be done in steps, they could be done in several steps, calculating the field strength 3 meters from the source, calculating the path loss to a point another 3 meters distant, calculating the field strength at that point, etc. This would give the unsupportable result that the field dropped by 34.74 dB every 3 meters. Over a distance of 30 meters, this incorrect method predicts that the field would decrease by 347.4 dB, making all signals inaudible. Even a 1,000,000 watt source would be below the noise of the universe after 21 meters, assuming that the RSL drops by 34 dB every 3 meters.

If one did this same calculation in 10-meter steps, one would calculate 45.2 dB every 10 meters, for a total loss of 135.6 dB over the same distance. Clearly, a method of predicting RSLs that gives impossible results and different results depending on the steps involved cannot be accurate.